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Facing the challenges of distribution systems operation with high wind power penetration

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Abstract—This paper addresses the challenges associated with the operation of a distribution system with high penetration of wind power. The paper presents some preliminary investigations of an ongoing Danish research work, which has as main objective to reduce the network losses by optimizing the reactive power flow in 60kV distribution networks through controlling the ability of wind power plants (WPPs) to generate or absorb reactive power. This paper aims to understand the characteristics of a distribution network with high penetration of distributed generation. A detailed analysis of the active and reactive power flows in a real distribution network under different wind and load conditions based on actual measurements is performed in order to understand the correlation between the consumption, wind power production, and the network losses. Conclusive remarks are presented, briefly expressing the track for the future work.

Index Terms—Distributed wind generation, distribution system, network loss, wind turbine capabilities

I. INTRODUCTION

According to Danish TSO, Energinet.dk, the total distributed generation (DG) installed capacity in Denmark in 2013 was around 6.6 GW where the wind turbines (WTs) had the highest share as 53% (3.5 GW) [1]. The integration of these WTs in the distribution networks offers several benefits, like reducing congestions and power losses in the transmission lines, active support in terms of voltage stability, improved load shedding [2] etc. Due to improvement in technologies and reducing costs, wind turbines are becoming prevalent choice among different DG options to support the network. This also has added benefit of low environmental impact. However, high penetration of DGs, like wind power and photovoltaic power PV, without control may also challenge operations of the distribution networks economically. For example, the electricity production from the WTs has an impact on the network losses that may change the reactive power flow and thus the variation of the voltage profile throughout the distribution feeders. Whenever there is excess power production from WTs compared to the consumption in the connected substation transformer, the network losses will be changed in

transformers and cables depending on the network topology. Furthermore, large concentration of WTs in the distribution network can also generate local power imbalances that have to be planked out/compensated in the 150/60kV transformer substations.

Relatively large reactive power can flow between 150kV and 60kV networks especially in high wind speed conditions [3]. This transfer of reactive power reduces the capacity of the lines causing network losses. To prevent large reactive power exchange between the distribution and transmission grids, the network operators impose explicit limits on reactive power flow through transformers. For instance, Energinet.dk has defined a regulation for the operational band for the reactive power exchange between the 60kV distribution and 150kV transmission networks [4]. The idea of such regulation is to ensure a reactive power balance and thus a stable voltage in the distribution network, limiting the losses caused by transport of active power. Additionally, these losses in 60 kV are not compensated by economic regulations.

Several studies have been done regarding impact of high penetration of distributed generation towards distribution system losses. Many studies have been done with respect to loss allocation with DG [5], [6]. Quezada et. al. [7] assess the qualitative nature of losses to understand the influence of DG penetration that affect annual losses variations. Costa and Matos [8] study the variation of losses due to the influences of distributed generation. Lund [9] presents an investigation of the active and reactive power losses in a distribution network with wind turbines and combined heat and power plants. Soder [10] and Mutale et. al. [11] proposed method to compute marginal losses per node. Shaloudegi et. al. [12] proposed a strategy for locational marginal price allocation based on loss allocation. All of these studies assume that the location and capacity of the DG in the MV network are known. However, there can be substantial amount of DG can be embedded in the LV network without the exact knowledge of location and capacity. Loss allocation can be challenging and inaccurate in such situations. Many studies have been performed regarding loss minimization in the distribution networks through optimal DG placement [13]–[16]. References [17]–[19] use network reconfiguration for minimizing loss in distribution system

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with high penetration of DG. Kalambe and Agnihotri [20] provide a survey for different loss minimization techniques in distribution network.

The goal of this paper is to address the challenges associated with the operation of a distribution system with high penetration of wind power by analyzing the impact of wind power generation on the distribution network losses based on real measurements. The characteristics of a specific distribution network are studied with respect to power flow, losses, generation and loads. The first step toward understanding how to reduce the network losses is to analyze the active and reactive power flow in the network by identifying where the power is produced in the network; where it is consumed and which controlled power resources are available. The aim of this paper is therefore to analyze the active and reactive power flow in a real distribution network under different wind and load conditions. Load flow calculations are performed based on a distribution grid model using the real-time measurements. All the studies are done without any reactive power support from controllable WPPs. Grid losses due to active and reactive power production from wind turbines are then calculated based on these load flow calculations. The study is carried out through simulations with a Danish distribution network model. The model, which is implemented in DigSilent PowerFactory, is validated and if necessary updated based on actual measurements in the distribution network. A method to estimate the network operational mode is developed based on "snap-shot" measurements.

II. DANISH RESEARCH PROJECT NETVIND

The overall objective of NetVind is to improve the operation of a real distribution network with a high penetration of wind power by exploiting WPP control capabilities. With an increased penetration of wind energy into the power distribution systems, the local network companies face many challenges in how to operate the distribution system by using WPPs as controllable components into the system. This means that WPPs should share some of the duties carried out today by the conventional power plants, such as regulating reactive power and performing voltage control on the grid.

The attention in the present research project is directed toward on how to reduce network losses due to transport of the active power additionally produced by wind turbines by optimizing the reactive power flow, and to reduce the loss of power production from WPPs during disconnections due to the repair and maintenance of the network. The research is done in two stages.

In the first stage, an offline analysis is performed as illustrated in Fig. 1 having as output a set of recommendations regarding algorithms to either: (I) to optimize the reactive power flow and thus minimize the power losses or (II) to reduce the loss of power production from WTs during disconnections due to the repair and maintenance of the network. A detailed analysis of the active and reactive power flow in a specific/realistic distribution grid under different wind and load conditions are performed based on simulations of a distribution grid model

and real measurements. Once the grid losses due to active and reactive power production from WPPs are calculated based on a series of load flow calculations through simulations with a Danish distribution network model, different optimization algorithms are analyzed through employing the ability of WTs to generate as well as absorb reactive power. Special attention in this project is on how the WPPs reactive power control capability can be used to control the flow of reactive power in the network, while voltage and grid load are kept within limits.

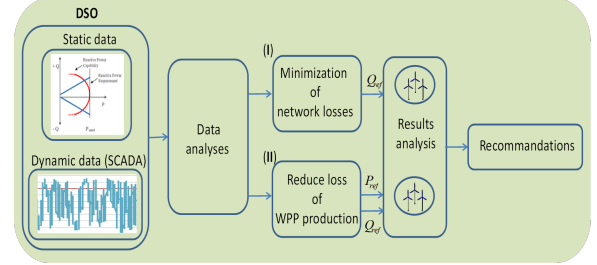


Fig. 1. Offline Analysis

The distribution system operator typically choose to shut down the WPPs in order to make sure that the network does not get overloaded during maintenance of network components like cables, transformers etc. However, in many of such situations it is sufficient to limit wind power production rather than shutting it down. The idea is to use the WPPs set-points to limit the wind power production while avoiding network congestions. As illustrated in Fig. 1, the first stage also investigates the potential for reduction of loss of wind power production rather than shutting it down during maintenance of the distribution network. Probable specific disconnections in the network will be analyzed for different wind and load conditions in the situation where the WPPs are ordered to shut down. The feasibility of using power set-points for the WPPs to ensure a reduction in wind power production and thereby prevent network overloading will be analyzed. Finally, the reduction of wind power production loss will be calculated.

In stage 2, the different algorithms developed in the offline analysis are implemented and validated online in a real distribution power system, as depicted in Fig. 2. The model, which is implemented in PowerFactory, will be validated and if necessary updated based on actual measurements in the distribution network.

III. DATA ANALYSIS

A. Network Model

Fig. 3 shows the 150/60kV distribution substation considered for the present investigations. It consists of following:

- 26 numbers of 60/10 kV substations which can be classified into 3 categories:
 - Substations which act as demands solely and consume active power.

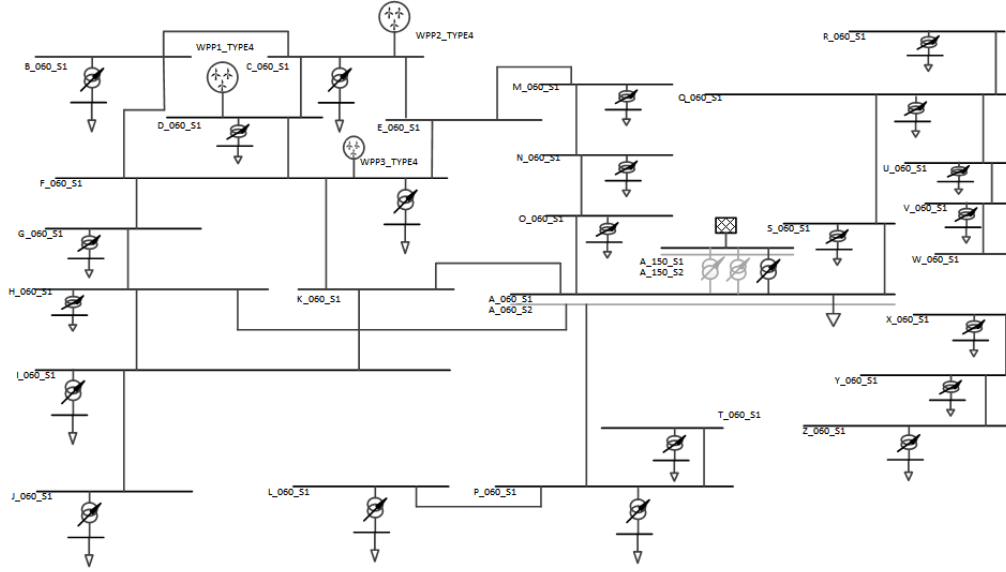


Fig. 3. 150kV Distribution Substation Model

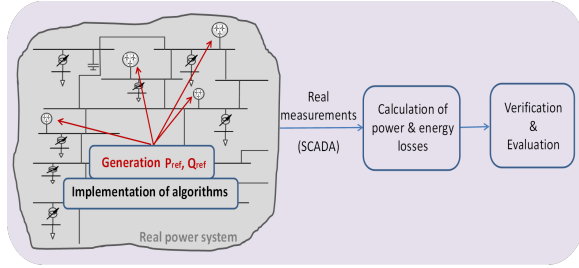


Fig. 2. Online Operation

in Table I.

TABLE I
SYSTEM CHARACTERISTICS

Max. Loading (Consumption) at 150 kV Substation (MW)	58.38
Avg. Loading at 150 kV Substation (MW)	-8.19
Max. Loading (Generation) at 150 kV Substation (MW)	103.04
Max. Wind Power Generation from Controllable WPPs (MW)	40.6
Avg. Wind Power Generation from Controllable WPPs (MW)	13.2

- Substations which behave as prosumers with uncontrollable generators connected at voltage levels less than equal to 10 kV.
- Substations which behave as prosumers with controllable WPPs connected at 60 kV. both as generator and demand. Henceforth, wind power generation from only these WPPs are referred in this paper.

- 3 controllable WPPs
- Loads and other generations (CHPs, PV etc.) are connected at 10 kV or lower voltage levels. These sources are aggregated together.

As depicted in Fig. 1, two types of data are available in the analysis:

- Static data which comprise of network topology data, transformer data, WPP data, P-Q capability curve of WTs etc.
- Dynamic data which consist of SCADA measurements of active power, reactive power, voltage and current from 150 kV and 60 kV bus bars and feeders.

In this paper, dynamic data from December 2014 to September 2015 at a resolution of 1 hour are collected and analyzed. The characteristics of these data are presented

In order to analyze the losses in the 60 kV feeders a simple methodology is used as described below.

B. Loss Calculation Methodology

The offline algorithm for loss calculation is as following:

- 1) Set time counter to zero
- 2) Receive active power, reactive power, voltage, current measurements for current hour
- 3) Run filtering and state estimation for filling missing data and eliminating measurement noise, bad data
- 4) Set active power, reactive power for PQ buses and active power, voltage for PV buses
- 5) Run power flow analysis
- 6) Calculate losses in 60 kV feeders
- 7) Increase time counter by 1 hour
- 8) Continue for the whole time series
- 9) Calculate energy losses and perform statistical data analysis

Statistical analyses of time series for load, wind power generation and power loss are performed to understand the behavior and correlation between these variables.

C. Timeseries Analysis

In order to understand the characteristics of the distribution network, P-Q plot for the total load connected at 10 kV are plotted in Fig. 4. Notice that when total active power load is negative i.e. demand is less than the generation connected at 10 kV; reactive power consumption is positive. This can be attributed to high penetration of uncontrollable fixed speed wind turbines connected below 10 kV. These kind of WTs consist of induction generators, which consume reactive power while generating active power.

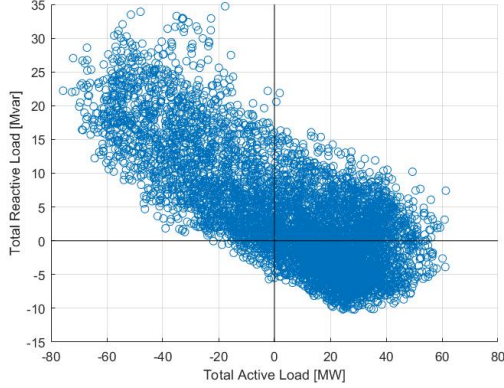


Fig. 4. P-Q plot for the total load connected at 10 kV

In order to understand the impact of wind power generation on network losses; a representative time series of active power loss and wind power generation for 450 hours are plotted in Fig. 5. Since the peaks of wind power generations are coordinated with the peaks of active power loss, Fig. 5 graphically suggests that high wind power generation might be driving the losses in this system.

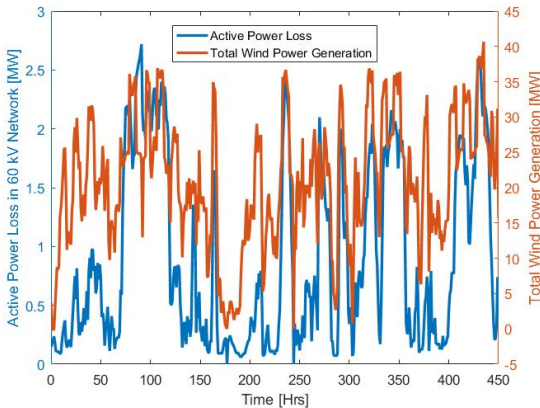


Fig. 5. Representative time series of active power loss and total wind power generation with 1 hour resolution

The probabilities of having losses greater or equal than 2MW for the actual wind power production (represented by capacity factor) is derived. Equation 1 calculates the probability of loss ≥ 2 MW, when each of the individual WPP

are operating at a specific capacity factor, CF_i (Equation 2). While, Equation 3 calculates the probability of loss ≥ 2 MW, when all the WPPs are operating at specific capacity factor, CF_{all} (Equation 4).

$$Pr_i(x) = Prob(loss \geq 2MW \mid CF_i = x \forall i = 1, 2, 3) \quad (1)$$

where,

$$CF_i = \frac{Gen_{WPP_i}}{Capacity_{WPP_i}} \forall i = 1, 2, 3 \quad (2)$$

$$Pr_{all}(x) = Prob(loss > 2MW \mid CF_{all} = x) \quad (3)$$

where,

$$CF_{all} = \frac{\sum_{i=1}^3 Gen_{WPP_i}}{\sum_{i=1}^3 Capacity_{WPP_i}} \quad (4)$$

These probabilities are plotted against specific capacity factor ($CF = x$) in Fig. 6. Pr_i and Pr_{all} follow more

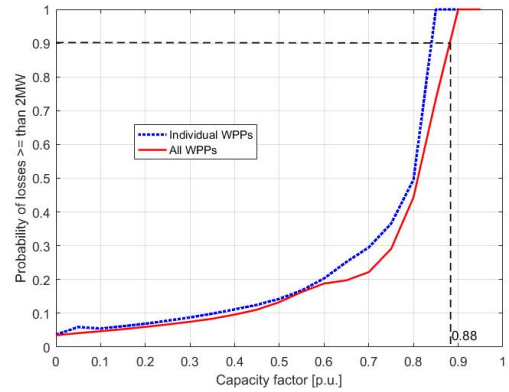


Fig. 6. Probability of loss ≥ 2 MW for different capacity factors

or less each other for CF lower than 0.6, while at higher CF, the probability of losses for individual WPPs is higher than the losses for CF for total wind power. Notice that, for capacity factor 0.8 and above, losses start increasing fast. For example, the probability of having these losses is 90% when the production is at least 88% of the rated capacity from all the WPPs.

It is also important to find the number of hours when WPPs are operating at high capacity factor. Duration curve for wind power generation is shown in Fig. 7. It can be observed that high wind power generation (capacity factor ≥ 0.5 i.e. 21 MW) only occurs for 1673 hours, i.e. only 24.9% of the total considered period. While capacity factor $\geq 0.7 = 29.4$ MW occurs only for 559 hours (8.3%). Duration curve for power loss in 60 kV network is shown in Fig. 8. It can be seen that, loss higher than 2 MW merely happens for 222 hours, i.e., 3% of the total considered period. Fig. 6, Fig. 7 & Fig. 8 show that high losses and high wind power generation occur for a relatively small portion of the total time.

Fig. 9 shows the number of hours WPPs are operated at different bins of capacity factors (CF_{all}). It can be seen that

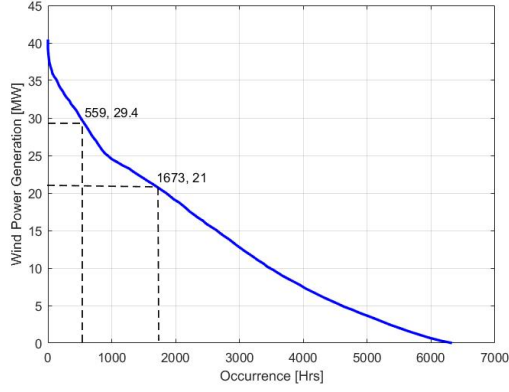


Fig. 7. Duration curve for Wind Power Generation

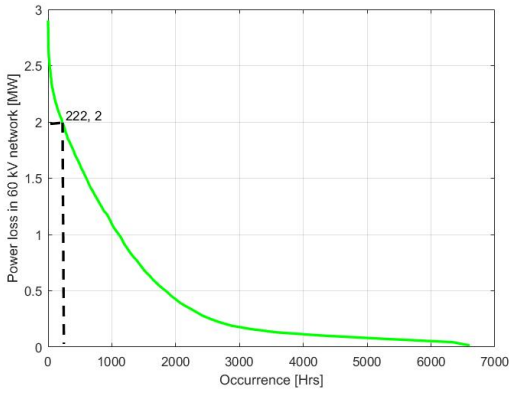


Fig. 8. Duration curve for power loss in 60 kV network

the WPPs operate for lower number of hours at high capacity factor as compared to low capacity factors. Fig. 10 shows the energy loss occurring in the 60 kV network for different bins of capacity factors of all WPPs (CF_{all}). For instance, energy loss is 341 MWh when WPP capacity factor is between [0.4 0.5]. It can be observed from the shaded region of Fig. 10 that major proportion of energy loss occurs when wind power generation is high (capacity factor ≥ 0.5), although number of hours are less for these capacity factors (Fig. 9). Table II provides the total energy loss in the system as well as energy loss during high and low wind power scenarios. Notice that 71% of the energy loss happen when wind power generation is more than 50% of its capacity.

TABLE II
ENERGY LOSS

Energy loss in the considered period (MWh)	3081
Energy loss during high wind power generation (MWh) (capacity factor > 50%)	2179
Energy loss during low wind power generation (MWh)	902

Another important point to be considered is the reactive power consumption by 60kV distribution network during

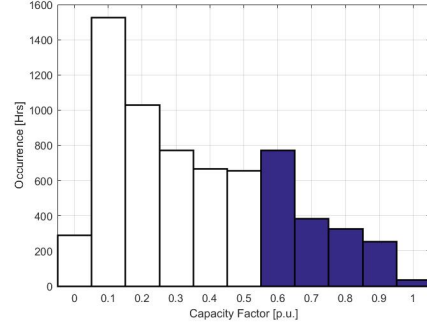


Fig. 9. Operational hours for WPPs at different capacity factors

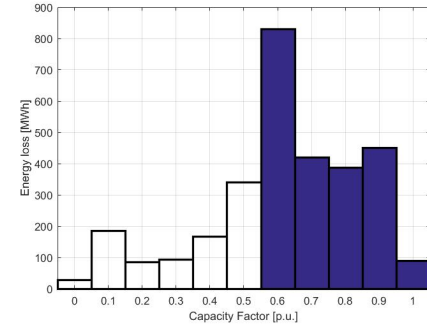


Fig. 10. Energy loss in the 60 kV network for different WPP capacity factors

different wind power scenarios. Scatter plot between reactive power consumption by 60 kV network and wind power generation is shown in Fig. 11. It is obviously clear from Fig. 11 that higher the wind power generation, the higher is reactive power consumption by the network. The reason for this is that the cables are highly loaded during high wind power scenarios resulting in increased consumption of reactive power. When wind power generation is low as well as system is lightly loaded, cables act as capacitors resulting in generation of reactive power by the distribution network.

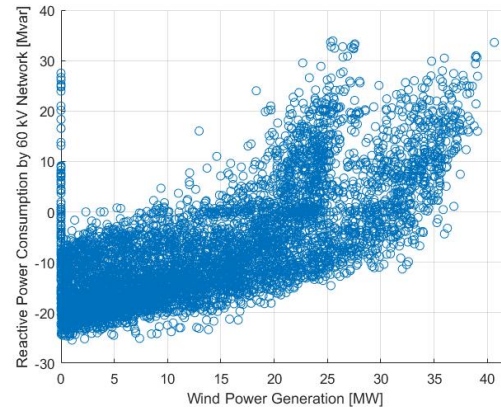


Fig. 11. Scatter plot between reactive power consumption by 60 kV network and wind power generation

High reactive power flow from transmission network can have many adverse effects like increased losses, low voltage, network congestion and may even result in voltage instability. It is advisable that the distribution system satisfies locally the reactive power requirements to avoid these situations.

It should be mentioned that all the above studies are done without any reactive power support from controllable WPPs. In the next step of the investigation, the control capabilities of WPPs will be used to minimize the losses. A set of requirements for WPPs are presented in the grid codes [21] require that the WPPs have certain reactive power generation capabilities in order to be connected to the system. Danish grid code requirements for reactive power control functions for a WPP is shown in Fig. 12. Reactive power generation capabilities from WTs are dependent on voltage and active power generation. However, WPPs may have additional controllable devices such as capacitor bank or shunt reactors to provide required reactive power capabilities.

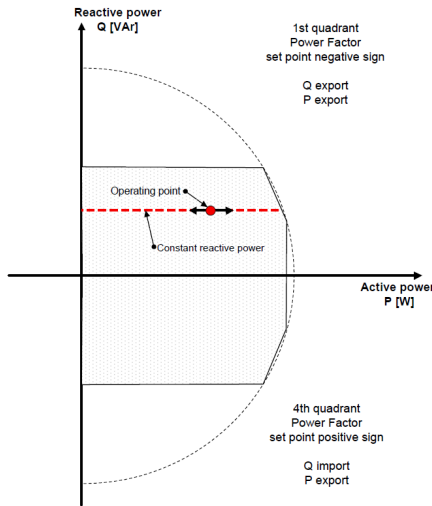


Fig. 12. Reactive power control functions for a wind power plant [21]

Currently there is no requirement for generating reactive power from the WPPs connected in Danish distribution systems. However, reactive power control from WPPs can be helpful in reducing network loss and improving voltage profile in active distribution network, this being in focus in the next step of present research.

IV. CONCLUSION

Time series of real measurements from a distribution system with high penetration of DGs are analyzed in this paper. The analysis has shown that the higher is wind power generation, the higher is network loss. Although high wind power generation occurs for small duration, it contributes for major proportion of energy loss. The results of this work can be used as a starting base in the next step of the investigation necessary to develop a methodology to minimize the losses in the distribution network by exploiting WPP capabilities to absorb or consume reactive power.

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